Restoring New Agegraphic Dark Energy in RS II Braneworld

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Abstract

Motivated by recent works [1, 2], we investigate new agegraphic model of dark energy in the framework of RS II braneworld. We also include the case of variable gravitational constant in our model. Furthermore, we establish correspondence between the new agegraphic dark energy with other dark energy candidates based on scalar fields.

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I. INTRODUCTION

An interesting attempt for probing the nature of dark energy (DE) is the so-called "agegraphic DE" (ADE). This model was recently proposed [3] to explain the acceleration of the universe expansion within the framework of a fundamental theory such as quantum gravity. The ADE model assumes that the observed DE comes from the spacetime and matter field fluctuations in the universe. Following the line of quantum fluctuations of spacetime, Karolyhazy et al. [4] discussed that the distance t in Minkowski spacetime cannot be known to a better accuracy than $\delta t = \beta t_p^{2/3} t^{1/3}$ where β is a dimensionless constant of order unity. Based on Karolyhazy relation and Maziashvili arguments [5], Cai proposed the original ADE model to explain the acceleration of the universe expansion [3]. Since the original ADE model suffers from the difficulty to describe the matter-dominated epoch, a new model of ADE was proposed by Wei and Cai [6], while the time scale was chosen to be the conformal time instead of the age of the universe. The ADE models have arisen a lot of enthusiasm recently and have examined and studied in ample detail [7–11].

Most researches on the DE puzzle remain in the standard four-dimensional cosmology. However, in recent years theories of large extra dimensions, in which the observed universe is realized as a brane embedded in a higher-dimensional spacetime, have received a lot of interest. According to the braneworld scenario, the standard model of particle fields is confined to the brane while, in contrast, the gravity is free to propagate in the whole spacetime [12]. In this theory the cosmological evolution on the brane is described by an effective Friedmann equation that is incorporated nontrivially with the effects of the bulk into the brane [13]. Apart from being closer to a higher-dimensional fundamental theory of nature, braneworld has also great phenomenological successes and a large amount of current research heads towards this direction. It is therefore desirable to extend ADE in the braneworld context. The investigations on the DE models in the context of braneworld scenarios have been carried out in [14, 15]. In the context of ADE, braneworld model with bulk-brane interaction has also been studied in [2].

In the present work we would like to restore new ADE (NADE) in RS II braneworld in the presence of varying gravitational constant. Employing the agegraphic model of DE in a non-flat universe, we obtain the equation of state (EoS) parameter for NADE density in the framework braneworld. We also investigate the correspondence between NADE and

scalar field models of DE such as quintessence, tachyon, K-essence and dilaton scalar fields and obtain the evolutionary form of these fields with varying G. There are significant indications that G can by varying, being a function of time or equivalently of the scale factor [16]. In particular, observations of Hulse-Taylor binary pulsar B1913 + 16 lead to the estimation $\dot{G}/G \sim 2 \pm 4 \times 10^{-12}\mathrm{yr}^{-1}$ [17, 18], while helio-seismological data provide the bound $-1.6 \times 10^{-12}\mathrm{yr}^{-1} < \dot{G}/G < 0$ [19]. Similarly, Type Ia supernova observations give the best upper bound of the variation of G as $-10^{-11}\mathrm{yr}^{-1} \leq \frac{\dot{G}}{G} < 0$ at redshifts $z \simeq 0.5$ [20], while astroseismological data from the pulsating white dwarf star G117-B15A lead to $\left|\frac{\dot{G}}{G}\right| \leq 4.10 \times 10^{-11}\mathrm{yr}^{-1}$ [21]. In addition, a varying G has some theoretical advantages too, alleviating the dark matter problem [22], the cosmic coincidence problem [23] and the discrepancies in Hubble parameter value [24].

This paper is organized as follows. In sections II and III, we review the formalism of NADE in RS II braneworld. In section IV, we study the NADE in braneworld with variable Newton's gravitational constant. In section V, we establish the correspondence between NADE model with other DE candidates based on scalar fields with the assumption that the gravitational constant G varies with time. The last section is devoted to conclusions and discussions.

II. NADE IN RS II BRANEWORLD

In this section, we apply the bulk NADE in general in RS II braneworld. The corresponding braneworld action is given by [1]

$$S = \int \mathrm{d}^5x\sqrt{-g}(M_5^3 R - \rho_{\Lambda 5}) + \int \mathrm{d}^4x\sqrt{-\gamma}(L_{br} - V + r_c M_5^3 R_4). \tag{1}$$

Here M_5 is the five dimensional Planck mass and R is the curvature scalar of the five dimensional bulk spacetime. Contrary to [1], we identify $\rho_{\Lambda 5}$ as the bulk NADE. Also g is the determinant of the five dimensional bulk spacetime metric while γ is the four-dimensional spacetime metric. The quantity V is called the brane tension and L_{br} is the brane matter content. Also r_c is a characteristic length scale while R_4 is the four dimensional curvature scalar.

The evolution of the brane is given by

$$H^2 + \frac{k}{a^2} = \frac{8\pi}{3M_p^2}\rho + \frac{8\pi}{3M_p^2}\rho_\Lambda. \tag{2}$$

Here $\rho = \rho_m + \rho_\Lambda$, the sum of energy density of matter and DE while $M_p^2 = (8\pi G)^{-1}$ is the reduced Planck mass. Following [1], the energy density of the four dimensional effective DE is given by

$$\rho_\Lambda \equiv \rho_{\Lambda 4} = \frac{M_p^2}{32\pi M_5^3}\rho_{\Lambda 5} + \frac{3M_p^2}{2\pi\left(\frac{L_5}{8\pi} - 2r_c\right)^2}. \tag{3}$$

Following [1], we have

$$\rho_{\Lambda 5} = c^2 \frac{3}{4\pi} M_5^3 L^{-2}. \tag{4}$$

Thus using (4) in (3), we obtain

$$\rho_\Lambda = \frac{3c^2}{128\pi^2} M_p^2 L^{-2} + \frac{3M_p^2}{2\pi\left(\frac{L_5}{8\pi} - 2r_c\right)^2}. \tag{5}$$

In order to use the above expression as the NADE, we replace $L = \eta$, i.e. the cut-off scale is taken as the conformal age of the universe defined by

$$\eta = \int_0^a \frac{\mathrm{d}a}{a^2 H}. \tag{6}$$

Following [1], we are interested in the restored ADE without bothering about bulk boundaries. Hence we take L_5 to be arbitrary large and ignore the second term in (5). We obtain

$$\rho_\Lambda = \frac{3c^2}{128\pi^2} M_p^2 \eta^{-2}. \tag{7}$$

From (2), we can write

$$1 + \Omega_k = \Omega_m + 2\Omega_\Lambda, \tag{8}$$

where we have used

$$\Omega_k = \frac{k}{(aH)^2}, \quad \Omega_m = \frac{8\pi\rho_m}{3M_p^2 H^2}, \quad \Omega_\Lambda = \frac{8\pi\rho_\Lambda}{3M_p^2 H^2}. \tag{9}$$

Using (7) and the last Eq. (9), we get

$$\Omega_\Lambda = \frac{c^2}{16\pi (H\eta)^2}. \tag{10}$$

Differentiating (7) w.r.t. t and using (10), we obtain

$$\dot{\rho}_\Lambda = -\frac{8H\rho_\Lambda}{ac}\sqrt{\pi\Omega_\Lambda}. \tag{11}$$

Differentiating (10) w.r.t. t, we obtain

$$\Omega_\Lambda' = -2\Omega_\Lambda\Big(\frac{\dot{H}}{H^2} + \frac{4}{ac}\sqrt{\pi\Omega_\Lambda}\Big), \tag{12}$$

where we have used $\dot{\Omega}_\Lambda = \Omega'_\Lambda H$. The energy conservation equations are

$$\dot{\rho}_\Lambda + 4H(1+\omega_\Lambda)\rho_\Lambda = 0, \tag{13}$$

$$\dot{\rho}_m + 4H\rho_m = 0. \tag{14}$$

Differentiating (2) w.r.t. t and using (11) and (14) yields

$$\frac{\dot{H}}{H^2} = -2 - \Omega_k + 4\Omega_\Lambda\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big). \tag{15}$$

Using (15) in (12), we get

$$\Omega'_\Lambda = 2\Omega_\Lambda\Big[\Omega_k + 2(1-2\Omega_\Lambda)\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big)\Big]. \tag{16}$$

From (11) and (13), we get

$$\omega_\Lambda = -1 + \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}. \tag{17}$$

The deceleration parameter is

$$q = -1 - \frac{\dot{H}}{H^2}, \tag{18}$$

which yields

$$q = 1 + \Omega_k - 4\Omega_\Lambda\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big). \tag{19}$$

III. NADE WITH INTERACTION

Assuming an interaction of NADE with matter, the energy conservation equations take the form

$$\begin{aligned} \dot{\rho}_\Lambda + 4H(1+\omega_\Lambda)\rho_\Lambda &= -Q, & (20)\\ \dot{\rho}_m + 4H\rho_m &= Q, & (21) \end{aligned}$$

where $Q = 4b^2H(\rho_m + 2\rho_\Lambda)$ is an interaction term, with b^2 is a coupling parameter. Thus from (11) and (20), we get

$$\omega_\Lambda = -1 + \frac{2}{ac}\sqrt{\pi\Omega_\Lambda} - \frac{b^2(1+\Omega_k)}{\Omega_\Lambda}. \tag{22}$$

IV. NADE WITH VARIABLE NEWTON'S GRAVITATIONAL CONSTANT

We now treat Newton's gravitational constant to be time dependent parameter, i.e. $G(t)$. Thus differentiating (7) w.r.t. t and using (10), we obtain

$$\dot{\rho}_\Lambda = -H\rho_\Lambda\Big(\frac{8}{ac}\sqrt{\pi\Omega_\Lambda} + \frac{G'}{G}\Big). \tag{23}$$

From (13) and (23), the EoS parameter becomes

$$\omega_\Lambda = -1 + \frac{2}{ac}\sqrt{\pi\Omega_\Lambda} + \frac{G'}{4G}. \tag{24}$$

Differentiating (2) w.r.t. t, and using (14) and (23) we get

$$\frac{\dot{H}}{H^2} = -2 - \Omega_k + 4\Omega_\Lambda\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big) + \frac{G'}{2G}(1 + \Omega_k - 2\Omega_\Lambda). \tag{25}$$

Using (25) in (12), we get

$$\Omega'_\Lambda = 2\Omega_\Lambda\Big[\Omega_k + 2(1 - 2\Omega_\Lambda)\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big) - \frac{G'}{2G}(1 + \Omega_k - 2\Omega_\Lambda)\Big]. \tag{26}$$

The deceleration parameter becomes

$$q = 1 + \Omega_k - 4\Omega_\Lambda\Big(1 - \frac{2}{ac}\sqrt{\pi\Omega_\Lambda}\Big) - \frac{G'}{2G}(1 + \Omega_k - 2\Omega_\Lambda). \tag{27}$$

V. CORRESPONDENCE BETWEEN NADE WITH SCALAR FIELD DE MODELS

Here like [10, 25], we suggest a correspondence between the NADE model with the quintessence, tachyon, K-essence and dilaton scalar field models in braneworld cosmology including varying G. To establish this correspondence, we compare the NADE density (7) with the corresponding scalar field model density and also equate the equations of state for this models with the EoS parameter given by Eq. (24).

A. New agegraphic quintessence model

The energy density and pressure of the quintessence scalar field ϕ are as follows [26]

$$\rho_Q = \frac{1}{2}\dot{\phi}^2 + V(\phi), \tag{28}$$

$$p_Q = \frac{1}{2}\dot{\phi}^2 - V(\phi). \tag{29}$$

The EoS parameter for the quintessence scalar field is given by

$$\omega_Q = \frac{p_Q}{\rho_Q} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}. \tag{30}$$

Here we establish the correspondence between the NADE scenario and the quintessence DE model, then equating Eq. (30) with the EoS parameter of NADE (24), $\omega_Q = \omega_\Lambda$, and also equating Eq. (28) with (7), $\rho_Q = \rho_\Lambda$, we have

$$\dot{\phi}^2 = (1 + \omega_\Lambda)\rho_\Lambda, \tag{31}$$

$$V(\phi) = \frac{1}{2}(1 - \omega_\Lambda)\rho_\Lambda. \tag{32}$$

Substituting Eqs. (7) and (24) into Eqs. (31) and (32), one can obtain the kinetic energy term and the quintessence potential energy as follows

$$\dot{\phi}^2 = \frac{3M_P^2 H^2 \Omega_\Lambda}{8\pi}\left(\frac{G'}{4G} + \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}\right), \tag{33}$$

$$V(\phi) = \frac{3M_P^2 H^2 \Omega_\Lambda}{8\pi}\left(1 - \frac{G'}{8G} - \frac{\sqrt{\pi\Omega_\Lambda}}{ac}\right). \tag{34}$$

From Eqs. (33) one can obtain the evolutionary form of the quintessence scalar field as

$$\phi(a) - \phi(a_0) = \sqrt{\frac{3}{8\pi}}\int_{a_0}^{a} M_p\left[\Omega_\Lambda\left(\frac{G'}{4G} + \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}\right)\right]^{1/2}\frac{\mathrm{d}a}{a}, \tag{35}$$

where a_0 is the scale factor at the present time.

B. New agegraphic tachyon model

The tachyon field was proposed as a source of the DE and inflation. A rolling tachyon has an interesting EoS whose parameter smoothly interpolates between -1 and 0 [27]. This discovery motivated to take DE as the dynamical quantity, i.e. a variable cosmological constant and model inflation using tachyons. The tachyon field has become important in string theory through its role in the Dirac-Born-Infeld (DBI) action which is used to describe the D-brane action [28]. The effective Lagrangian density of tachyon matter is given by [28]

$$\mathcal{L} = -V(\phi)\sqrt{1 + \partial_\mu\phi\partial^\mu\phi}. \tag{36}$$

The energy density and pressure for the tachyon field are as following [28]

$$\rho_T = \frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}, \tag{37}$$

$$p_T = -V(\phi)\sqrt{1-\dot{\phi}^2}, \tag{38}$$

where $V(\phi)$ is the tachyon potential. The EoS parameter for the tachyon scalar field is obtained as

$$\omega_T = \frac{p_T}{\rho_T} = \dot{\phi}^2 - 1. \tag{39}$$

If we establish the correspondence between the NADE and tachyon DE, then equating Eq. (39) with the EoS parameter of NADE (24), $\omega_T = \omega_\Lambda$, and also equating Eq. (37) with (7), $\rho_T = \rho_\Lambda$, we obtain

$$\dot{\phi}^2 = \frac{G'}{4G} + \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}, \tag{40}$$

$$V(\phi) = \frac{3M_P^2H^2\Omega_\Lambda}{8\pi}\left(1 - \frac{G'}{4G} - \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}\right)^{1/2}. \tag{41}$$

From Eq. (40), one can obtain the evolutionary form of the tachyon scalar field as

$$\phi(a) - \phi(a_0) = \int_{a_0}^{a}\frac{\mathrm{d}a}{Ha}\left(\frac{G'}{4G} + \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}\right)^{1/2}. \tag{42}$$

C. New agegraphic K-essence model

It is also possible to have a situation where the accelerated expansion arises out of modifications to the kinetic energy of the scalar fields. In this context, the K-essence scalar field model of DE is used to explain the observed late-time acceleration of the universe. The K-essence is described by a general scalar field action which is a function of ϕ and $\chi = \dot{\phi}^2/2$, and is given by [29, 30]

$$S = \int \mathrm{d}^4x\sqrt{-\mathrm{g}}\; p(\phi,\chi), \tag{43}$$

where $p(\phi,\chi)$ corresponds to a pressure density as

$$p(\phi,\chi) = f(\phi)(-\chi + \chi^2), \tag{44}$$

and the energy density of the field ϕ is

$$\rho(\phi,\chi) = f(\phi)(-\chi + 3\chi^2). \tag{45}$$

The EoS parameter for the K-essence scalar field is obtained as

$$\omega_K = \frac{p(\phi,\chi)}{\rho(\phi,\chi)} = \frac{\chi - 1}{3\chi - 1}. \tag{46}$$

Equating Eq. (46) with the EoS parameter (24), $\omega_K = \omega_\Lambda$, we find the solution for χ

$$\chi = \frac{1 - \frac{G'}{8G} - \frac{\sqrt{\pi\Omega_\Lambda}}{ac}}{2 - \frac{3G'}{8G} - \frac{3\sqrt{\pi\Omega_\Lambda}}{ac}}. \tag{47}$$

Using $\dot{\phi}^2 = 2\chi$ and (47), we obtain the evolutionary form of the K-essence scalar field as

$$\phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{\mathrm{d}a}{Ha} \left(\frac{2 - \frac{G'}{4G} - \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}}{2 - \frac{3G'}{8G} - \frac{3\sqrt{\pi\Omega_\Lambda}}{ac}} \right)^{1/2}. \tag{48}$$

D. New agegraphic dilaton model

The dilaton scalar field model of DE is obtained from the low-energy limit of string theory. It is described by a general four-dimensional effective low-energy string action. The coefficient of the kinematic term of the dilaton can be negative in the Einstein frame, which means that the dilaton behaves as a phantom-type scalar field. However, in presence of higher-order derivative terms for the dilaton field ϕ the stability of the system is satisfied even when the coefficient of $\dot{\phi}^2$ is negative [31]. The pressure (Lagrangian) density and the energy density of the dilaton DE model is given by [31]

$$p_D = -\chi + c' e^{\lambda\phi}\chi^2, \tag{49}$$

$$\rho_D = -\chi + 3c' e^{\lambda\phi}\chi^2, \tag{50}$$

where c' and λ are positive constants and $\chi = \dot{\phi}^2/2$. The EoS parameter for the dilaton scalar field is given by

$$\omega_D = \frac{p_D}{\rho_D} = \frac{-1 + c' e^{\lambda\phi}\chi}{-1 + 3c' e^{\lambda\phi}\chi}. \tag{51}$$

Equating Eq. (51) with the EoS parameter (24), $\omega_D = \omega_\Lambda$, we find the following solution

$$c' e^{\lambda\phi}\chi = \frac{1 - \frac{G'}{8G} - \frac{\sqrt{\pi\Omega_\Lambda}}{ac}}{2 - \frac{3G'}{8G} - \frac{3\sqrt{\pi\Omega_\Lambda}}{ac}}, \tag{52}$$

then using $\dot{\phi}^2 = 2\chi$, we obtain

$$e^{\frac{\lambda\phi}{2}}\dot{\phi} = \left(\frac{2 - \frac{G'}{4G} - \frac{2\sqrt{\pi\Omega_\Lambda}}{ac}}{c'\left(2 - \frac{3G'}{8G} - \frac{3\sqrt{\pi\Omega_\Lambda}}{ac}\right)} \right)^{1/2}. \tag{53}$$

Integrating with respect to a, we get

$$e^{\frac{\lambda\phi(a)}{2}}=e^{\frac{\lambda\phi(a_0)}{2}}+\frac{\lambda}{2\sqrt{c'}}\int_{a_0}^{a}\frac{\mathrm{d}a}{Ha}\left(\frac{2-\frac{G'}{4G}-\frac{2\sqrt{\pi\Omega_\Lambda}}{ac}}{2-\frac{3G'}{8G}-\frac{3\sqrt{\pi\Omega_\Lambda}}{ac}}\right)^{1/2}. \tag{54}$$

Therefore the evolutionary form of the dilaton scalar field is obtained as

$$\phi(a)=\frac{2}{\lambda}\ln\left[e^{\frac{\lambda\phi(a_0)}{2}}+\frac{\lambda}{\sqrt{2c'}}\int_{a_0}^{a}\frac{\mathrm{d}a}{Ha}\left(\frac{1-\frac{G'}{8G}-\frac{\sqrt{\pi\Omega_\Lambda}}{ac}}{2-\frac{3G'}{8G}-\frac{3\sqrt{\pi\Omega_\Lambda}}{ac}}\right)^{1/2}\right]. \tag{55}$$

VI. CONCLUSIONS AND DISCUSSIONS

In this work we studied the NADE model in the framework of RS II braneworld scenario and restored the EoS as well as the deceleration parameters in a non-flat universe. Then, we extended our study to the case where the gravitational constant G varies with time. A varying G has some theoretical advantages such as alleviating the dark matter problem [22], the cosmic coincidence problem [23] and the discrepancies in Hubble parameter value [24]. We also established a correspondence between NADE and quintessence, tachyon, K-essence and dilaton energy density in the braneworld scenario including varying G. We adopted the viewpoint that these scalar field models of DE are effective theories of an underlying theory of DE. Thus, we should be capable of using these scalar field models to mimic the evolving behavior of the NADE and reconstructing the scalar field models according to the evolutionary behavior of the NADE. Finally, We reconstructed the potentials and the dynamics of these scalar field models which describe quintessence, tachyon, K-essence and dilaton cosmology.

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